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A. HERTZBERG
J. GORDON HALL
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FOREWORD

This interim technical report was prepared by the Aerodynamic Research Department of Cornell Aeronautical Laboratory, Inc., Buffalo, New York, on Contract AF 33(657)-8860 for the Aerospace Research Laboratories, Office of Aerospace Research, United States Air Force. The research reported herein was accomplished on Task 7065-07, "Hypervelocity Flight Duplication Techniques", Project 7065, "Aerospace Simulation Techniques Research" under the technical cognizance of Mr. Robert G. Dunn of the Fluid Dynamics Facilities Research Laboratory of ARL.

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ABSTRACT

A new approach to generating high-velocity air flows with very low ambient dissociation levels is discussed. Briefly, the approach utilizes a nonsteady isentropic compression wave which is focused through an area contraction to accelerate and compress the test gas. This processed gas may be used directly as a test medium or may be allowed to expand nonsteadily through the expansion wave which appears at the focal point of the compression wave system. In either case, the flow may be further expanded in a nozzle if so desired. The advantages and disadvantages of both methods of operation are discussed.

The problem of generating the required wave motion is presented in some detail and preliminary studies of several possible driving techniques are summarized.

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INTRODUCTION

Although shock-tube facilities have been developed in recent years in which high velocities (exceeding 25,000 ft/sec, say) may be produced,[1-3] the chemical composition of the shock-processed test flow differs significantly from that of ordinary air. That is, significant quantities of N, O, and NO are produced, as well as significant ionization when the shock speed is sufficiently high. Of course, there are aerodynamic flows of interest in which the chemical composition of the ambient stream is not greatly important. However, there are also problems of interest for which the ambient composition is important. In the latter case, the desired ambient stream composition is usually that of ordinary air which is appropriate to atmospheric flight over a wide altitude range.

The problem of producing a very high velocity air flow having the chemical composition appropriate to flight is exceedingly difficult. Intensive development work is currently under way on at least two types of devices: the expansion tube[4, 5] and the electromagnetic accelerator.[6] In principle, at least, these devices are capable of producing high-velocity airflows with lower dissociation than can be obtained with conventional shock-tube and shock-tunnel techniques. However, there are practical problems associated with the development of both devices, and it will undoubtedly be some time before either emerges as a useful aerodynamic tool.

The purpose of this paper is to describe a theoretical study of a new approach to the problem which is capable, in principle, of producing very high velocity air flows of still lower dissociation than obtainable with the above methods. This approach utilizes a nonsteady, isentropic compression wave to accelerate and compress the test gas as illustrated in Fig. 1, which is a schematic wave diagram for a focused wave in a constant area duct. The test gas, which is initially at rest, is compressed and accelerated by the compression wave system generated by the moving piston. The piston is assumed to move in such a way that the compression wave system is focused at a single point downstream of which a shock wave, an expansion wave, and an interface originate. The resultant piston motion is characterized by a monotonically increasing acceleration.[7] Once the desired test-flow conditions have been attained at the piston face, the piston acceleration drops abruptly to zero and a uniform flow is established between the piston and the tail of the compression wave system. If desired, this slug of compressed gas (test region 1 in Fig. 1) may be expanded steadily in a nozzle or, alternatively, may be expanded nonsteadily (to test region 2) by the downstream traveling-expansion wave which originates at the focal point of the compression wave. This nonsteady expansion is particularly attractive, because it can significantly increase the total enthalpy of the flow. The fluid in test

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region 2 of Fig. 1 also may be further expanded in a nozzle. Since there is no diaphragm involved, the interface which forms the downstream boundary of test region 2 may be somewhat better behaved than that normally encountered in shock-tube flows.

If the wave were not properly focused, the interface would be replaced by a region of nonuniform entropy with a thickness determined by the scale of the shock-formation process. The result would be a loss of test time in both regions 1 and 2.

Of course, the nonsteady, isentropic compression wave is not a new motion in a fundamental sense. Its mathematical and physical properties have been known for many years.[8] Furthermore, in Ref. 9 it is pointed out that this motion is responsible for the transient shock-speed overshoot which has been observed in shock tubes for years.[10,11] However, the purposeful application of a focused isentropic compression wave to aerodynamic testing, in view of its potential ability to produce very high velocity air flows with low dissociation levels, appears to be new.

The discussion which follows is divided into five principal sections. The first deals mainly with the influence of isentropic compression on the ambient test flow dissociation level, which is representative of the effect on the flow chemistry in general. In the second section, the effects of compressing the flow through an area contraction are discussed, with particular emphasis on the large improvement in testing time which is thereby obtained. Properties of the piston trajectory for a single, discontinuous tube contraction are described in the third section. The fourth section discusses the large amplification of stagnation pressure and velocity which results when an area contraction is used. Finally, a preliminary study of theproblem of producing the required piston trajectory is summarized in the fifth section.

REDUCTION OF TEST GAS DISSOCIATION

The dissociation level of the ambient test flow provides a convenient index of the departure of the test flow chemical composition from that of ordinary air. For given total enthalpy and initial state of the test gas, the final dissociation level is reduced, if the process by which the gas is compressed and accelerated is made more isentropic. This is caused by two effects. First, the final density level is increased by a more isentropic process and therefore dissociation is suppressed. Second, the accelerating process becomes more efficient, with the result that the kinetic energy of the flow is increased at the expense of the thermal energy for a fixed total enthalpy. This can be seen by comparing the respective flow Mach numbers for shock and isentropic compression obtained in the limit of infinite compression. When the specific heat ratio is 1.4, the limiting Mach number for a shock wave is 1.89, which compares with 5.0 for the nonsteady isentropic compression. Thus, for given total enthalpy, the ratio of kinetic to internal energy, which is proportional to the square of the Mach number, is about seven times greater for the isentropic compression than for the shock wave.

The advantages of isentropic compression in this respect are illustrated graphically in Figs. 2 and 3. A nonsteady, isentropic compression is compared to a single shock wave in Fig. 2, which is a plot of test flow pressure versus temperature for equilibrium air initially at 300°K and 10 psia. Also superimposed on the plot are parametric curves of constant limiting velocity and atomic mass fraction in test test region 1. The results of this figure indicate that the dissociation level corresponding to a given limiting velocity is much less for an isentropic than for a shock compression. For example, an isentropic compression will produce a 30,000 ft/sec. flow in test region 1, which has a dissociation level of less than 1%, while the corresponding shocked flow will be about 50% dissociated.

The pressures indicated in Fig. 2 for the isentropic compression are very high, but can be lowered by reducing the initial pressure. While this tends to increase the dissociation level, the basic advantage of isentropic compression, as compared to a shock compression, still remains. The effect of initial pressure is illustrated in Fig. 3 for the isentropic compression of equilibrium air from an initial temperature of 300°K. Curves of constant limiting velocity and atomic mass fraction appropriate to test region 1 are also shown. Therefore, the temperature, pressure, and dissociation level in test region 1 can be determined from the desired limiting velocity and initial pressure. It is evident, from this figure, that low dissociation levels at high limiting velocities can be obtained without excessively high final pressures. However, the initial pressure required to duplicat the isentropic stagnation pressures of lunar reentry in region 1 is about 10^{-5} atm. and it appears, from Fig. 3, that there would be significant dissociation at this condition.

This problem is not so severe for region 2 because of the large velocity increase which occurs through the nonsteady expansion wave. The magnitude of the velocity increase is illustrated in Fig. 4, where the velocities in both test regions 1 and 2 are plotted against the Mach number of the shock wave which originates at the focal point. The curves shown were calculated for an ideal gas. However, real gas effects are small, as is illustrated by the equilibrium points shown on the figure. Presumably, this is a result of the thermal energy being small compared to the kinetic energy of the flow.

In particular, the results of Fig. 4 indicate that a 40,000 ft/sec. limiting velocity in region 2 corresponds to about a 26,000 ft/sec. limiting velocity in region 1. Therefore, the results of Fig. 3 indicate that such a 40,000 ft/sec. flow could be produced in region 2 with a dissociation level of about 1% and pressures less than a few thousand atmospheres.

Thus far, dissociation has been the only real-gas effect discussed. Another important effect, even for relatively low enthalpy conditions, is NO formation. The equilibrium NO concentration is strongly dependent on temperature and reaches a maximum value somewhat above 3000°K. The maximum value increases somewhat with pressure. However, the NO mole fraction at 3000°K remains constant at about 0.05. Below 3000°K, the NO concentration falls rapidly with decreasing temperature.

Consequently, assuming chemical equilibrium, the temperature in region 1 could not greatly exceed about 3000°K, if both the dissociation level and the NO concentration are to be small. The curves shown in Fig. 3 imply that this condition cannot be met at high velocity in region 1, regardless of the initial pressure.

In region 2, lower NO concentrations can be achieved, even if the chemical composition freezes through the expansion wave. In particular, the curves of Figs. 3 and 4 indicate that an initial pressure of about 10^{-3} to 10^{-4} atm. is required if flow velocities of the order of 35,000 ft/sec. were desired in region 2, while the temperature in region 1 was not to exceed 3000°K. This is consistent with the initial pressure required to duplicate the isentropic stagnation condition of lunar reentry conditions in region 2.

THE NONUNIFORM AREA TUBE

While an isentropic compression greatly suppresses test gas dissociation, it unfortunately yields a small testing time per unit tube length. This is a penalty which arises whenever the compression process is made more isentropic, because then the density rise is increased and mass conservation requires that the tube length needed to produce a given flow of specified duration must be increased. The density ratio for an isentropic compression may be several orders of magnitude greater than that for a shock wave which produces the same flow velocity. Consequently, enormous tube lengths, orders of magnitude greater than that of conventional shock tubes, would be required to produce any useful testing time for an isentropically compressed gas in a constant area tube at large flow velocities. For example, the results shown in Fig. 5 indicate that the tube length required to produce a 30,000 ft/sec. flow for about 100μsec. would be about 6 miles.

This problem can be greatly alleviated by performing the compression in a nonuniform area tube. In this case, the available testing time can be derived from mass-flow considerations under the assumptions that the flow remains isentropic and that a uniform flow exists corresponding to region 1 of Fig. 1. The result is that the testing time in region 1 is increased by the ratio of the volumes of the nonuniform and uniform tubes for the same focal length, L, and test-flow cross-sectional area. Consequently, the testing time can be increased by making the average area of the nonuniform tube greater than that of the constant-area tube, as indicated in Fig. 6. For example, a 100μsec. flow at 30,000 ft/sec. could be produced with a focal length of about 200 ft. (rather than 6 miles for the constant-area tube) if the tube were constructed of two equal-length segments with an area ratio of about 300 to 1. Although it would appear that the tube length could be further reduced by increasing the area ratio, a detailed consideration of the wave processes involved, as discussed below, indicates that, in general, the testing time is limited by the arrival of waves generated at the area discontinuity. Therefore, beyond this time, the flow is not uniform and the argument given above is no longer valid.

The assumption that the flow remains isentropic in the nonuniform tube is basic to the conclusion that an area contraction can be used to increase the testing time for a given tube length. This assumption has been examined in detail by constructing several wave diagrams whose properties have been discussed elsewhere[12, 13] and will be briefly reviewed here.* The wave diagrams were constructed by working upstream from the focal point, using the method of characteristics under the assumption of one-dimensional flow.[7, 14]

An area nonuniformity generates families of reflected waves such as those shown in Fig. 6 for the particular case of a discontinuous area contraction. Consequently, the wave diagram is fundamentally different from that of a constant-area tube. As long as the flow in the smaller tube is subsonic, the only family of waves originating at the discontinuity is a family of reflected compression waves which move upstream in the large-diameter tube, tending to decelerate the flow. These waves are reflected from the piston prior to formation of a shock wave in all of the cases considered. Therefore, the flow is isentropically processed in the large-diameter tube.

Ultimately, the Mach number at the entrance to the small-diameter tube reaches its limiting value of 1 and additional waves arise from propagate downstream into this tube. These waves are expansion waves which arise from the condition that the flow sufficiently near the focal point must become supersonic eventually, while sonic flow is the limiting condition at the entrance of the small-diameter tube. Consequently, a nonuniform tube can be used to increase the testing time significantly without altering the isentropic character of the flow.

When the contraction ratio is sufficiently large, the wave motion in the large-diameter tube becomes insensitive to its magnitude. That is, to a good approximation, most of the flow behaves as if the tube were closed. The only part of the wave diagram which is significantly influenced in any way is the region very near the discontinuity where the velocity, which is very small, is sensitive to the contraction ratio. Consequently, the most important effect of the contraction ratio arises in the final stages of the piston motion. Thus, the major effect of the contraction ratio is on the arrival time of the piston at the discontinuity.

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*The authors are indebted to R. Weatherston and G. Rudinger of the Aerodynamic Research Department of CAL for their aid in clarifying certain aspects of the wave-diagram analysis.

With regard to the testing-time limitation referred to earlier, Fig. 6 indicates that the uniformity of the test flow in region 1 ends with the arrival of the first expansion wave generated at the discontinuity. It should be noted that this limitation depends on the location of the area discontinuity only, and cannot be removed by introducing a larger contraction ratio. Consequently, the time duration of the flow in region 1 always has a definite upper limit. This limit is a rapidly decreasing function of flow velocity, as indicated in Fig. 7, where it can be seen that a 30,000 ft/sec. flow can be produced for, at most, about 200 μ sec. in a 200 ft. tube. While this value may seem small, it is considerably larger than the 5 to 10 μ sec. times which are currently obtained in shock tubes[1-3] at this velocity.

For a given focal length, additional tube lengths are required in order to obtain a usable testing time in region 2. For example, the results of Fig. 8 indicate that about 35 additional feet would be required for each 100 μ sec. of testing time in region 2 at a flow velocity of about 40,000 ft/sec. However, the testing time per unit additional tube length in this region is greater than the maximum testing time in region 1 per unit focal length. Consequently, this suggests that a greater testing time can be obtained at a given flow velocity in a tube of fixed total length by reducing the focal length of the wave system and testing in region 2, rather than region 1. Of course, in practice, the behavior of the interface will be an important factor in determining the useful testing time in region 2.

PISTON TRAJECTORY CHARACTERISTICS

The piston path required for production of the focused compression wave in a tube with a discontinuous area contraction is shown in Fig. 6. It is evident that the piston path in this case differs considerably from that for the constant-area tube shown qualitatively in Fig. 1. Initially, the piston accelerates toward the area change, but later it decelerates until a very low velocity (and deceleration) is attained just upstream of the discontinuity. At this point, the gas ahead of the piston is being compressed quasi-steadily to a good approximation. Once the desired test conditions are obtained, the piston deceleration must fall abruptly to zero, so that essentially a stagnant reservoir is established on the upstream side of the area discontinuity. A small and constant velocity of the piston must be maintained in order to supply the small-diameter tube with the constant mass flow rate required. Eventually, the piston enters the small tube and must accelerate such that no further waves are generated as it overtakes the expansion waves generated earlier at the area discontinuity. Finally, the piston moves past the focal point at high velocity.

Obviously, in practice, that part of the piston path in the small-diameter tube would be very difficult to produce. Fortunately, the problem can be avoided by stopping the piston at the area change. In this case, the flow in the small-diameter tube will resemble the flow in a suddenly closed duct with expansion waves propagating into the small-diameter tube, as shown schematically in Fig. 9. The disadvantage of this scheme is that some of the testing time is lost because not all of the processed gas becomes useful test flow. This means that a larger area contraction is necessary to produce a given testing time in a tube of given length. This can be appreciated from Fig. 9 by noting that the expansion waves produced when the piston is stopped have a higher velocity than that of the original piston path. Consequently, the test time can be the same in both cases only if the piston reaches the discontinuity later, at a time when it is stopped. This can be accomplished only if the mass of the gas to be compressed, and therefore the area of the large-diameter tube, is increased. Wave diagram calculations indicate that the necessary area increase is not excessive.

The ratio of the length of the large-diameter tube to the focal length, L_0/L, has a significant effect on the piston path. This point will be discussed more fully in the section on driving techniques.

VELOCITY AND STAGNATION PRESSURE AMPLIFICATION

There are two features of the wave motion in the contracted-area tube which should be emphasized. The first is the large flow velocities which are obtained with relatively small piston velocities. The ratio of the flow velocity to the maximum piston velocity has no theoretical limit.

The second feature is the large isentropic stagnation pressure produced in the test flow for a comparatively small maximum pressure on the piston face. In particular, the ratio of these quantitites approaches a finite limit of 7.81 and 529 in test regions 1 and 2, respectively, for infinite flow velocity, and an ideal gas with specific heat ratio 1.4. The significance of this is that high ambient densities, corresponding to low altitudes, could be obtained at high velocities without having to contain excessively high pressures. For example, the maximum isentropic stagnation pressure needed to duplicate the conditions experienced during the reentry of a typical lunar-mission vehicle is about 2×10^4 atm. This could be produced with maximum pressures on the piston face of the order of 4000 and 400 atm. for regions 1 and 2, respectively.

DRIVING TECHNIQUES

The development of the isentropic compression tube as a practical aerodynamic tool obviously depends on finding an adequate driving mechanism. In many respects, the problem of obtaining the desired piston path is similar to that which has arisen in the design of an optimum performance gun, and which has apparently been studied theoretically in only the last few years. However, there is a significant difference. In a gun, usable performance is obtained with large deviations from the optimum piston path, while this is not the case for the isentropic compression tube.

Like the constant base-pressure gun, there are several features of the piston trajectory described above which makes its production by mechanical means a difficult task. For instance, the time scale of the motion is relatively short for a mechanical device, being of the order of tenths of a second. Furthermore, the pressure on the piston face toward the end of its motion is characterized by a very rapid rise, while the velocity and acceleration of the piston is quite low. This implies that the force driving the piston must nearly equal the force exerted by the pressure acting on the piston face, and consequently must also show a very rapid rise. Furthermore, in the section on the characteristics of the piston trajectory, it was indicated that the piston deceleration must vanish discontinuously near the area change, once the desired test conditions have been established. Consequently, the net force on the piston must also vanish discontinuously at this point. This implies that the force driving the piston must rise instantaneously to equal the force acting on the piston face.

In addition, since the piston must decelerate toward the end of its motion, an external braking force must be applied when the piston becomes sufficiently massive. This becomes clear when the required base pressure (that immediately behind the piston) history is calculated for a specified piston mass. The results of such a calculation are shown in Fig. 10 for the particular case where L_D/L is .20. The required base pressure has been normalized with respect to its initial value, which depends on both the piston mass and the initial pressure of the gas to be compressed. When the piston mass parameter, β, is zero (β is proportional to the ratio of the piston mass to the mass of the gas to be compressed), the base pressure equals the face pressure, which is a monotonically increasing function of time. On the other hand, when β is very large, the effect of the face pressure becomes vanishingly small over most of the piston trajectory. Consequently, the value of P_B/P_{Bi}, the normalized base pressure, approaches that of $\bar{a}/\bar{a}_i$, the normalized acceleration, where $\bar{a}_i$ and P_{Bi} are the initial values of the piston acceleration and the base pressure, respectively. Therefore, negative base pressures, which imply an externally applied braking force, must arise for very heavy pistons, since decelerations occur. Curves are shown in Fig. 10 for intermediate masses. It appears that an external braking force is required for all but the very lightest of pistons.

The magnitude and point of application of the braking force is influenced by the value of L_D/L, as indicated in Fig. 11, where the normalized piston acceleration history, which (as indicated above) approximates the normalized base pressure history of a massive piston, is plotted with L_D/L as a parameter. As this figure implies, the effect of decreasing L_D/L is to decrease the magnitude of the required braking force and shift its application to an earlier time. This is also true of the maximum acceleration.

Although the braking force can be large in cases of practical interest, it is small compared to the force required to drive the piston against the area discontinuity at the end of the piston trajectory. The latter force is very large for the extreme conditions of lunar reentry, particularly if test region 1 is used. In this case, the maximum pressure on the piston face is about 4000 atm. Consequently, if the small-tube area were about 1 sq. in., and an area contraction ratio of 10^3 employed, the force on the piston face would be about 6×10^7 lbs. The situation for testing in region 2 is somewhat better, because the maximum pressure required is only about 400 atm. This implies that the maximum force on the piston would have a lower bound of about 6×10^6 lbs.

The above force value for region 1 is probably too small because the initial pressure required is of the order of 10^{-5} atm. As a result, viscous effects may dictate that the smaller tube have an area considerably greater than 1 sq. in. On the other hand, the force value given above for region 2 is more reasonable because the required initial pressure is much higher ($\sim 10^{-3}$ atm.) and therefore viscous effects will not be as important. Consequently, smaller tube diameters will be needed for region 2 than for region 1 at the same flow conditions.

The combination of large forces, large rates of change in the magnitude and direction of the applied forces, and a short time scale makes the mechanical design of a driving mechanism a difficult problem. In this connection, several possible schemes have been examined. In particular, throttling valve pressure regulators, electromagnetically accelerated pistons, variable mass pistons, "leaky" pistons, pneumatic and hydraulic braking mechanisms, "rotating" pistons and various combinations of these schemes have been studied. None are free from obvious practical objections, and no completely satisfactory method has been found to date, although several of the techniques appear promising. In the following discussion, a brief summary is given of each of these methods.

Throttling Valve

In the throttling valve scheme, the base pressure of the piston is regulated by valve through which mass flows into the volume behind the piston at an appropriate rate. As indicated in the previous section, the proper piston path can be obtained in this way only when the piston mass is very low. Otherwise, a means of braking the piston motion is required. For duplication of lunar reentry conditions, the maximum allowable piston mass turns out to be very small and essentially implies that only a membrane of very light material is permitted. However, there is a more serious objection which essentially eliminates the throttling valve from consideration. Namely, enormous mass flow rates are required toward the end of the piston motion in order to obtain the proper rate of pressure rise in such a large volume at high pressure. For reasonable inlet areas, this implies that either the density of the entering flow must be very high, which means that the pressure in the reservoir supplying the valve must also be very high, or else the velocity of the entering flow must be very high, which requires that the reservoir temperature be very high. In both cases, unreasonably large values of reservoir pressure and/or temperature are required.

Variable-Mass Piston

In the variable-mass piston approach, the desired acceleration history is obtained by suitably varying the piston mass while the base pressure is maintained constant. The difficulty with this approach is that impossibly large piston-material densities are required at certain times. This remains a problem, even if some base pressure regulation is allowed.

"Leaky" Piston

The "leaky" piston technique is a variation of what is termed the "leaky" gun technique in Ref. 15. In this method, no attempt is made to constrain the piston to move on the path required to produce a focused wave. Instead, the piston is allowed to move in some easily obtained trajectory (for example, that produced by a constant base pressure), while a programmed leak through either the piston or the tube walls compensates for the difference between the actual and the desired trajectory. This method has the advantage of being capable of producing the required high pressures during the piston "bounce" at the area discontinuity, while requiring a base pressure of only a few atmospheres. However, a difficulty with this scheme is that there are portions of the piston trajectory in which mass must be added to the gas being compressed, rather than removed. The physical reason for this result is apparently that it is not possible to satisfy simultaneously the pressure at the "bounce" and the condition that the pressure on the piston face be greater than that for no leakage. This last condition is essential if there is to be mass removal only. It is satisfied in the optimum gun problem, and this is why it was possible to conclude, in Ref. 15 and in Ref. 16, that the method is attractive for improving gun performance. However, the method does not seem suited to the isentropic compression tube, even when the mass of the piston is allowed to vary, unless the mass injection problem can be avoided.

Another variation on the "leaky" gun idea has also been discussed in Refs. 15 and 16. In this method, a number of disc-like slots of varying depth are cut into the wall of the tube. As the piston moves through the tube, gas is trapped in the slots that are sealed off by the piston and the trapped gas no longer participates in the compression process. Analysis in the present study has indicated that mass injection is also necessary with this scheme.

Hydraulic or Pneumatic Braking

The braking force which is required when the piston becomes sufficiently heavy could possibly be supplied by pneumatic or hydraulic mechanisms. However, the displacements involved are generally quite large and structural difficulties would be expected, particularly if compressive stresses in the connecting bar become large.

Electromagnetic Acceleration

Another possibility is a crossed-field electromagnetic accelerator in which a current flows through the piston to an external resistive load in a direction perpendicular to an applied magnetic field. The magnitude of the retarding force could be varied by changing the resistance of the external circuit or by properly distributing the magnetic field strength. As long as a retarding force is required, no external current supply is required, since the generator effect is sufficiently strong that the required braking forces can be obtained with reasonably small values of the magnetic induction ($\sim 10^3$ gauss).

The piston force required at the area discontinuity is considerably greater than the braking force. Thus, a significantly larger magnetic field strength is required in this region. Furthermore, a driving force is required which implies that the current must be supplied by an external source. The results of preliminary calculations indicate that lunar reentry conditions in region 2 could be attained with high, but not unreasonable, values of the magnetic induction and current, e.g., about 10^5 gauss and 5×10^6 amps, respectively. The resultant potential difference across the piston is of the order of 50 volts. The maximum power requirement (excluding that for the magnetic field) is of the order of 250 megawatts, and the total energy required is of the order of 5×10^6 joules. These values indicate that this may be a practical method for duplicating lunar reentry in region 2. However, it does not appear possible to use the method to produce the same conditions in region 1, since the force on the piston would be about 10 times greater than that for region 2. This force increase can only be achieved by increasing the current, since 10^5 gauss is about the limit of current magnetic technology. Thus, the required current would be of the order of 5×10^7 amps, while the power and energy needed would be about 2.5×10^4 megawatts and 5×10^8 joules. These values do not appear practical.

The physical size of the magnetic field region would be quite large but comparable with that for MHD generators. Consequently, the magnetic power requirements would be about the same, since the field strengths are comparable.

"Rotating" Piston

Another possibility is the "rotating" piston approach which, in practice, would consist of a piston with an internally mounted flywheel. Exchange of rotational and translational energy would be effected by means of a threaded shaft along which the piston would move. The motion of the piston would be controlled by the pitch of the thread. A preliminary examination of this method has indicated that the parameters in the problem can be so chosen that reasonable flywheel angular velocities result. In particular, it appears that the rotational speed can be held to the order of 1000 r.p.m. However, the primary problem with this method is the large forces which are involved. Again, it appears that lunar reentry conditions might be obtained in region 2 but not in region 1.

Double Piston Method

Another attractive scheme consists of two pistons, one mounted inside the other, with the internal pressure on one side of the inner piston controlled by a throttling valve in the external piston. Since a relatively small volume is involved, most of the objections to a throttling valve mechanism do not apply. Furthermore, it appears that a relatively small driving pressure could be used. At the present time, this method is the only one of those studied which may be capable of producing lunar reentry conditions in region 1.

CONCLUSIONS

The isentropic compression tube is capable, in principle, of producing very-high-velocity airflows with low dissociation. Testing-time limitations can be greatly reduced by compressing the flow through an area contraction, rather than in a constant-area tube. This gives rise to additional families of waves which do not alter the isentropic nature of the flow.

Two test regions have been discussed. In region 1, the gas has been processed by the nonsteady compression wave, while in region 2, it has also been expanded nonsteadily through the wave which is formed at the focal point of the compression-wave system. The advantages of testing in region 2 rather than in region 1 are considerable. These are that lower piston face pressures are required for the same velocity and isentropic stagnation pressure, lower dissociation can be obtained, smaller tube diameters are needed, and the test time per unit tube length is greater. A possible disadvantage is that the test flow follows an interface which may adversely affect the testing time and the flow uniformity.

Of particular significance is the large velocity and stagnation pressure amplifications which arise by virtue of the nonsteady wave processes. As a result of these effects, very high velocity conditions could be produced at high piston speeds or the problem of containing excessively high pressures.

The required piston path has been discussed and shown to be a difficult one to produce mechanically. To data, only a few promising driving mechanisms have been found, and only one of these is appropriate for producing lunar reentry conditions in region 1. This scheme is a two-piston arrangement where one piston is mounted inside the other. The appropriate piston motion is obtained by controlling the pressure differential across the internal piston, possibly by a valve in the outer piston.

The prospects of producing lunar reentry flow conditions in region 2 are considerably brighter. In this case, the preliminary analysis summarized here has indicated two possibilities, in addition to the two-piston method mentioned above. These are the crossed-field accelerator and the screw-mounted "rotating" piston. However, additional study is needed before the feasibility of these schemes is established.

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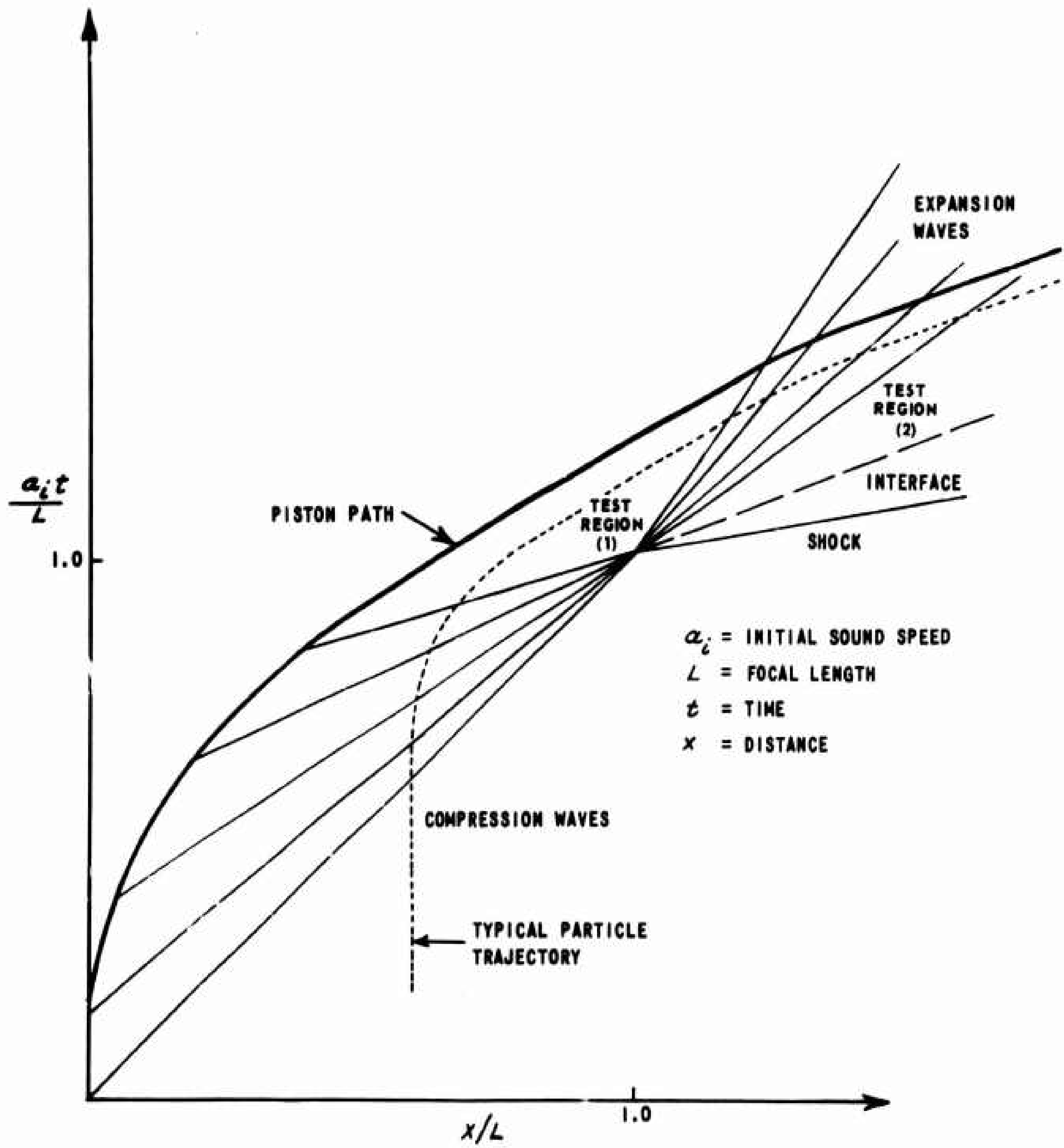

Figure 1 SCHEMATIC DIAGRAM OF FOCUSED ISENTROPIC COMPRESSION WAVE IN A CONSTANT AREA DUCT

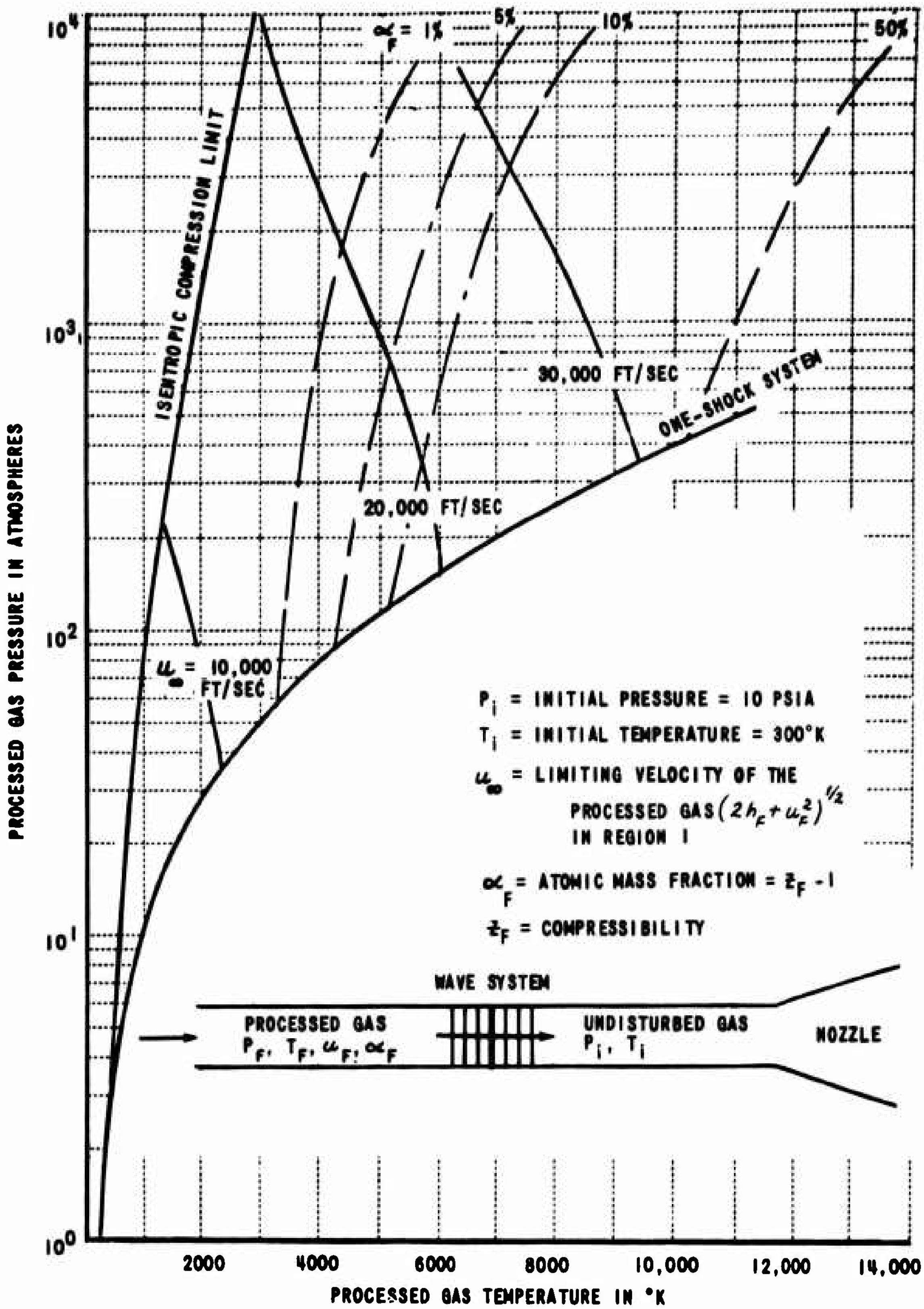

Figure 2 EFFECT OF WAVE CONFIGURATION ON THE DISSOCIATION LEVEL OF EQUILIBRIUM AIR

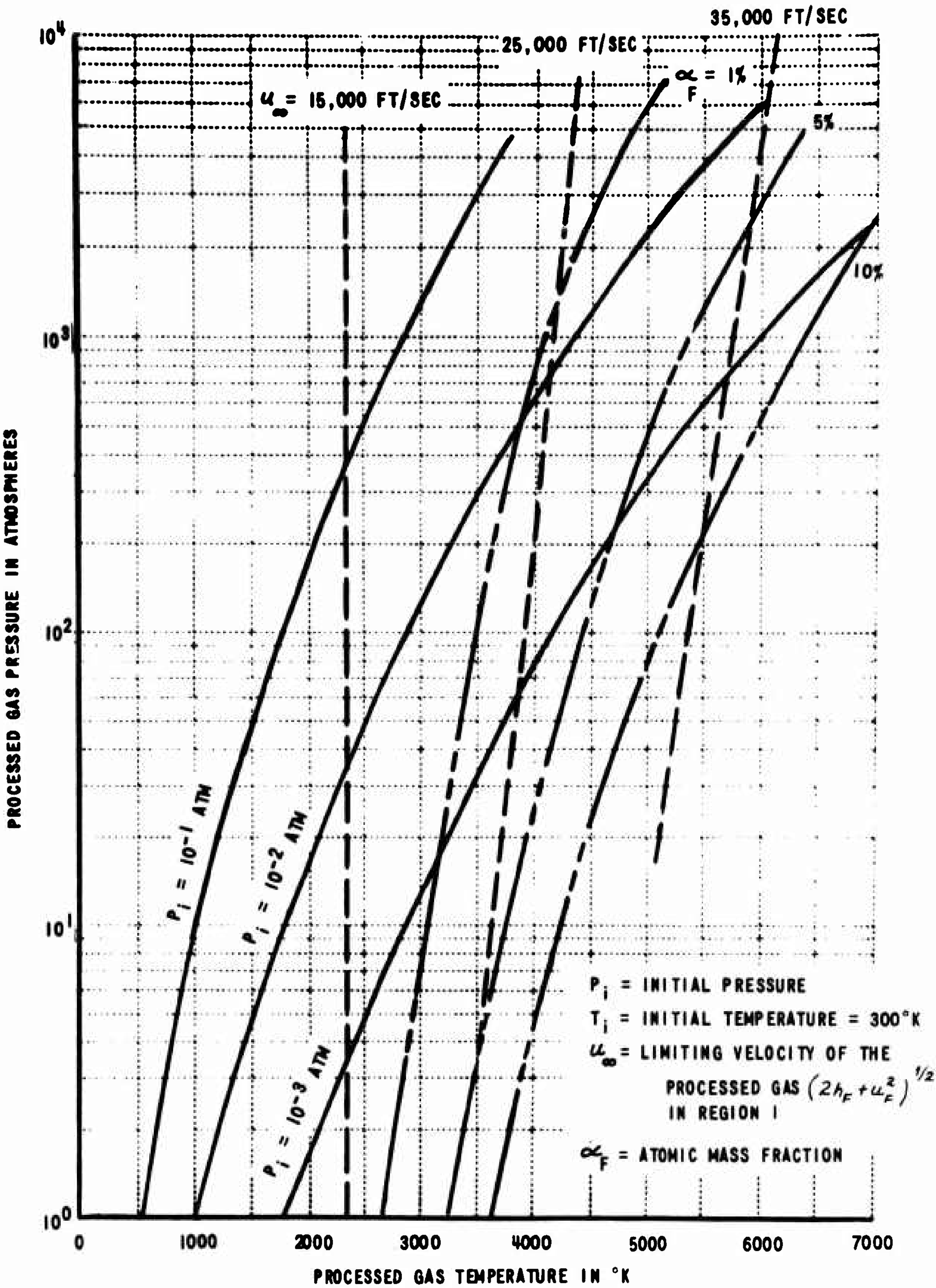

Figure 3 PERFORMANCE MAP FOR ISENTROPIC COMPRESSION OF EQUILIBRIUM AIR (TEST REGION I)

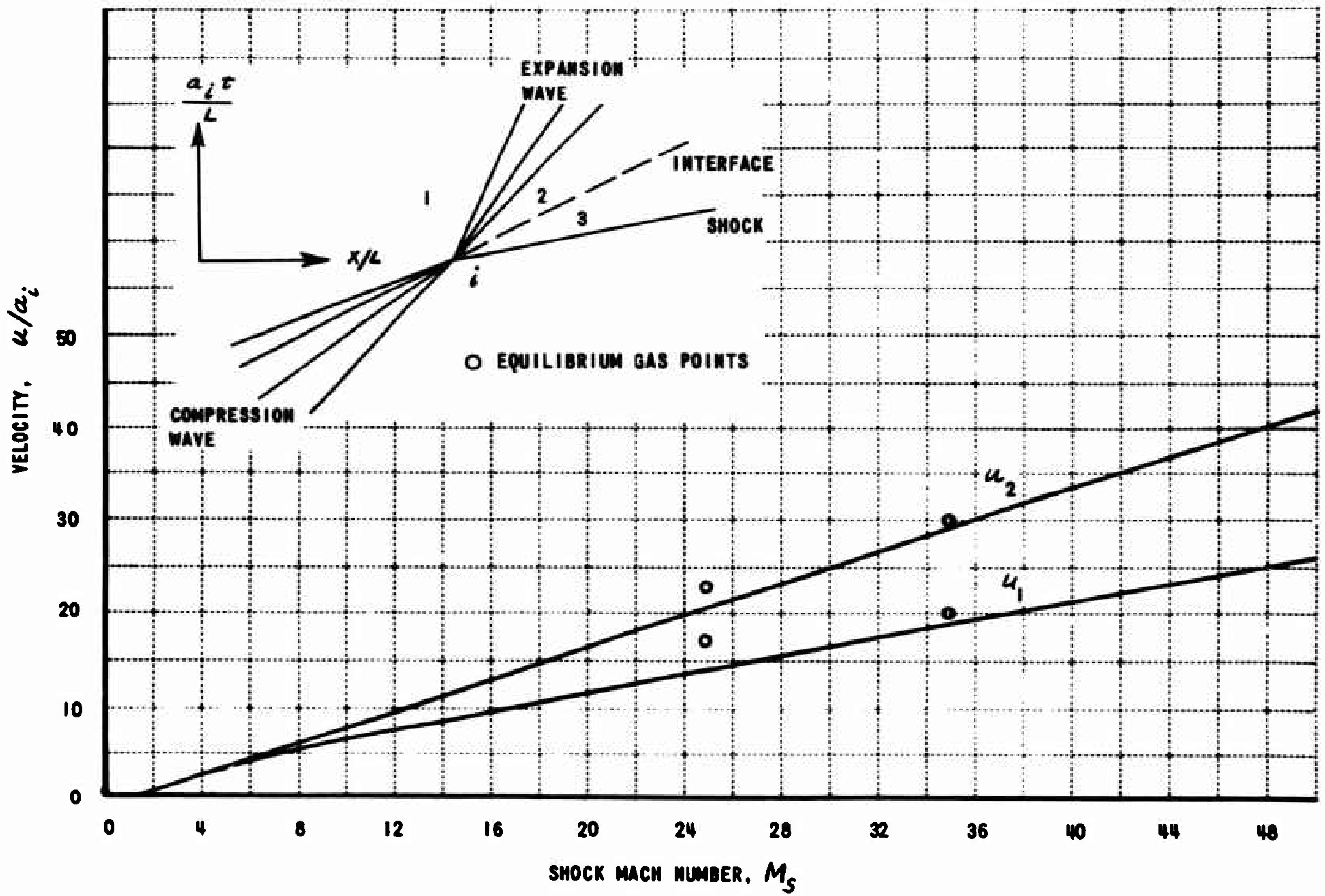

Figure 4 VELOCITY INCREASE THROUGH THE NONSTEADY EXPANSION WAVE FOR AN IDEAL GAS, $\gamma = 1.4$

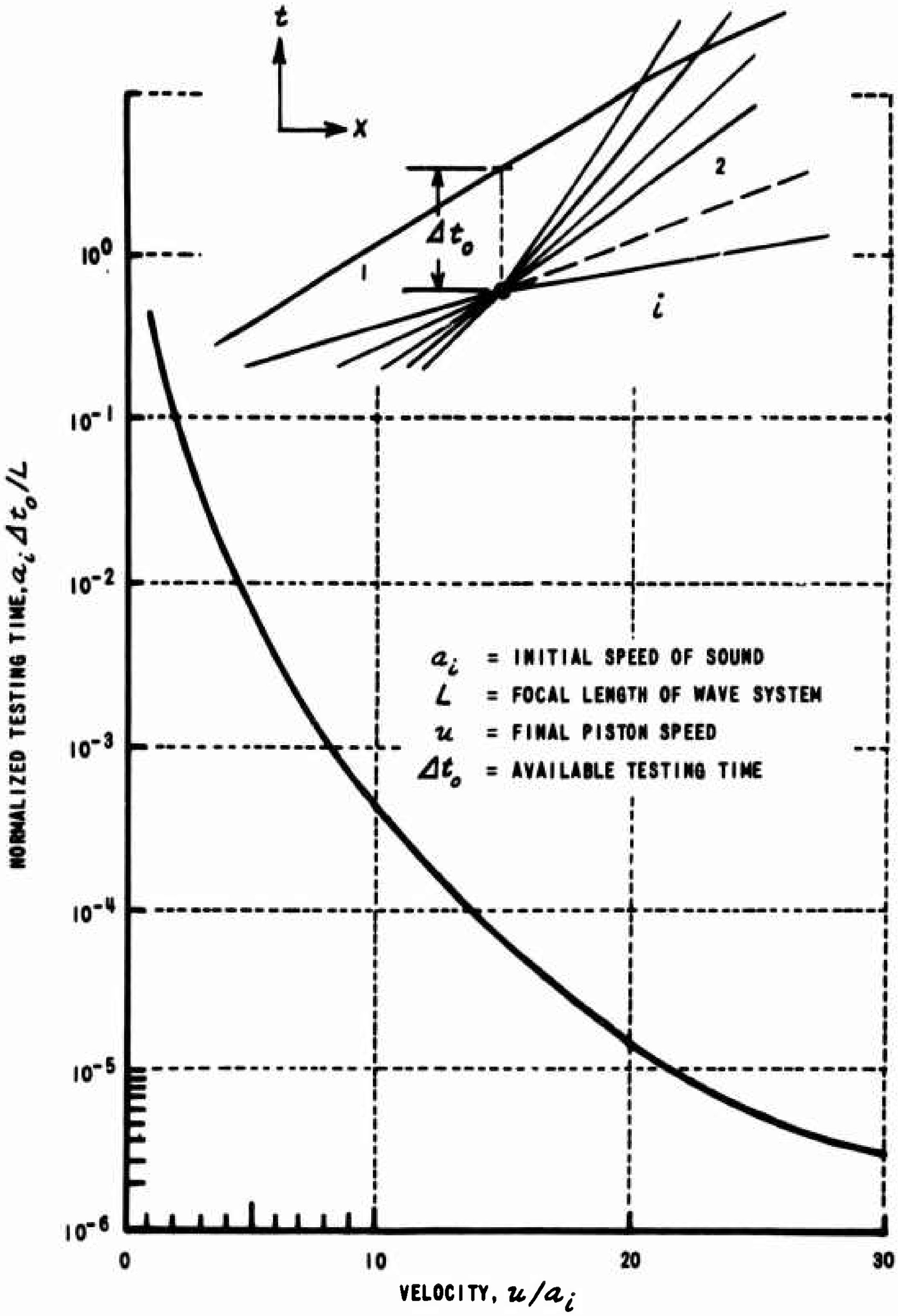

Figure 5 AVAILABLE TESTING TIME IN A CONSTANT AREA TUBE AS A FUNCTION OF FLOW VELOCITY IN REGION I FOR AN IDEAL GAS, $\gamma = 1.4$

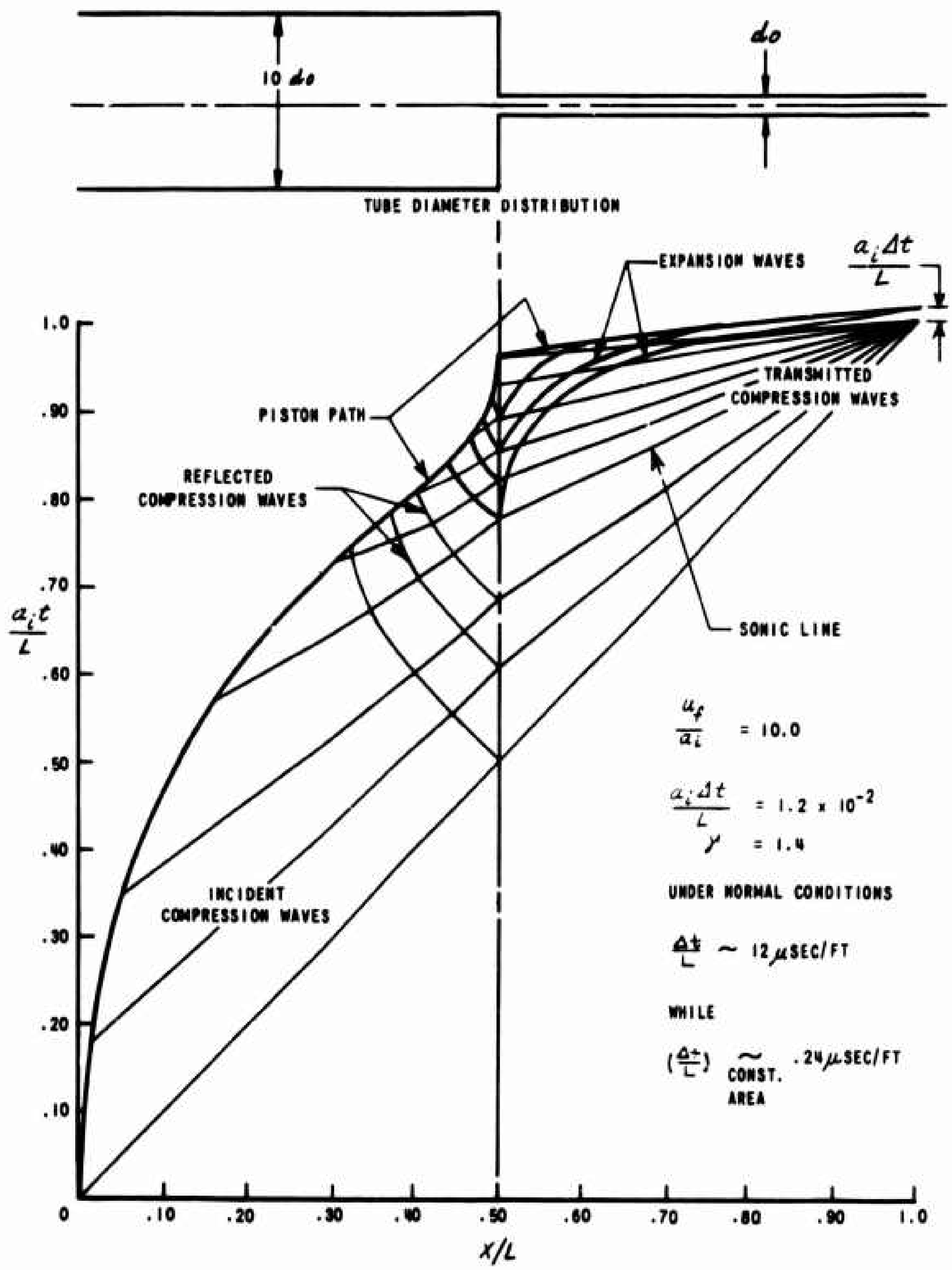

Figure 6 WAVE DIAGRAM FOR A CENTERED COMPRESSION WAVE IN A DUCT WITH A DISCONTINUOUS CONTRACTION

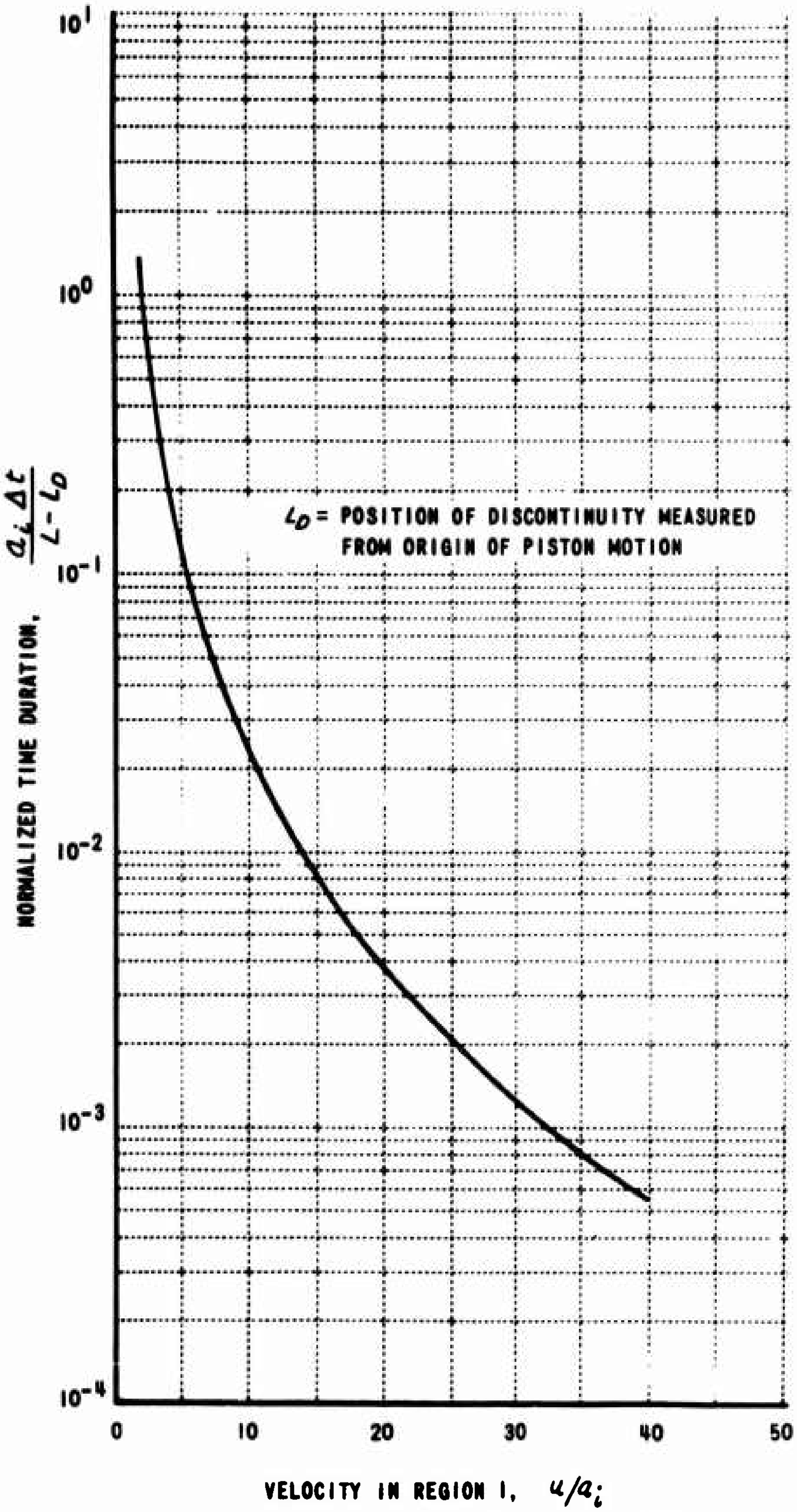

Figure 7 MAXIMUM DURATION OF UNIFORM FLOW IN REGION I FOR AN IDEAL GAS, $\gamma = 1.4$

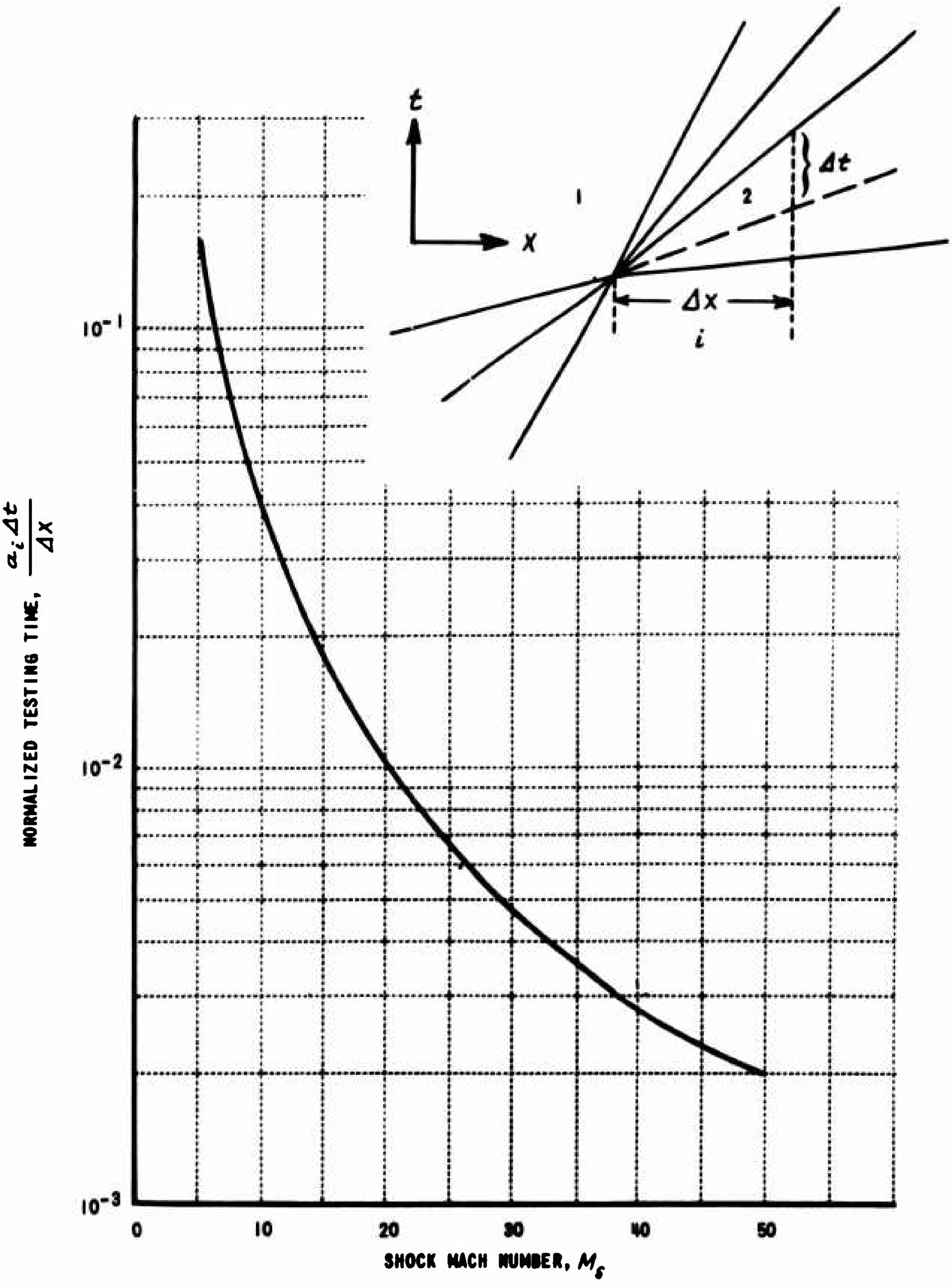

Figure 8 TESTING TIME IN REGION 2 AS A FUNCTION OF SHOCK MACH NUMBER FOR AN IDEAL GAS, $\gamma = 1.4$

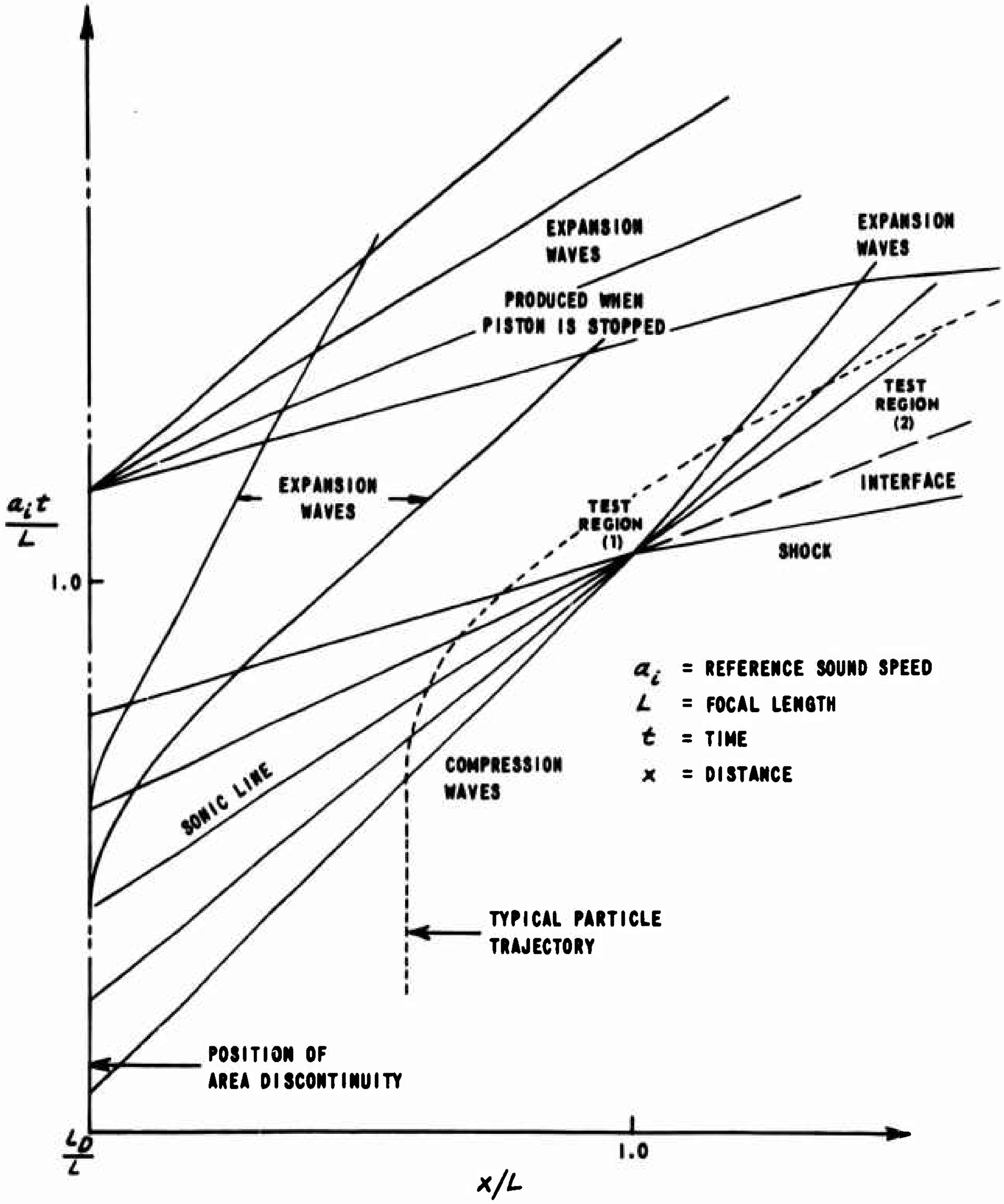

Figure 9 SCHEMATIC WAVE DIAGRAM OF THE FLOW IN THE SMALL DIAMETER TUBE WHEN THE PISTON IS STOPPED AT THE DISCONTINUITY

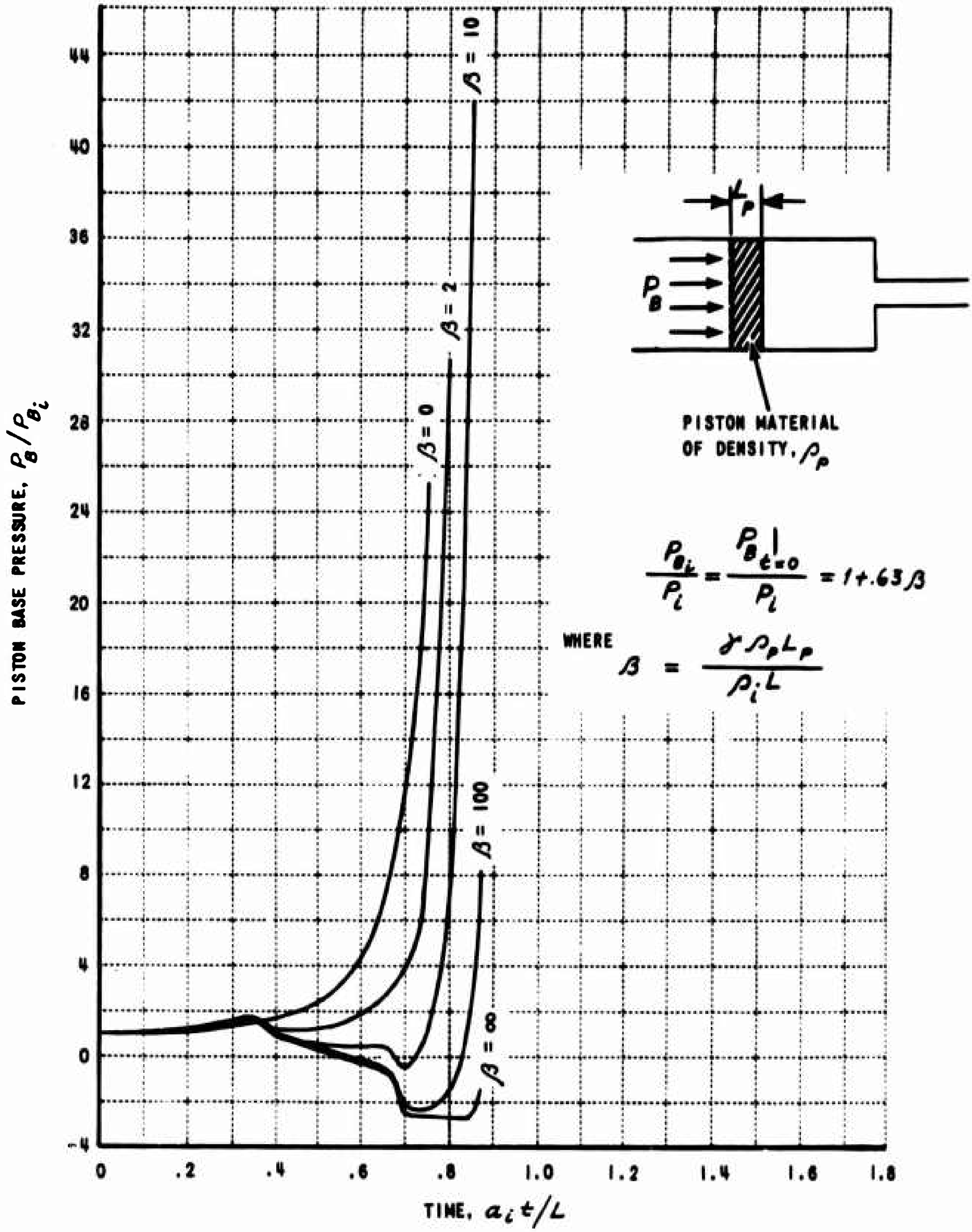

Figure 10 THE EFFECT OF PISTON MASS ON INSTANTANEOUS BASE PRESSURE, $L_D/L = .20$

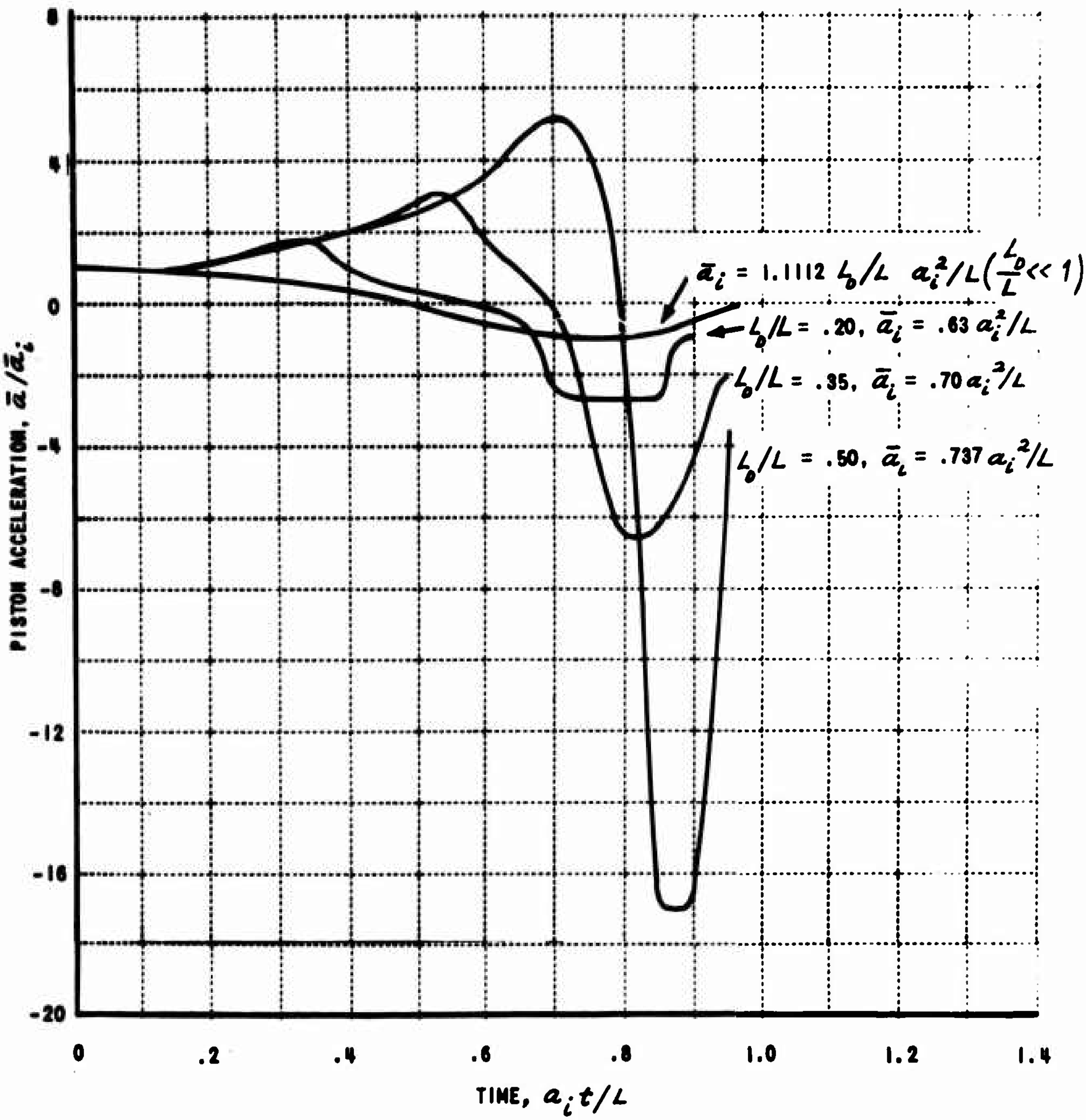

Figure 11 THE EFFECT OF L_D ON THE PISTON ACCELERATION HISTORY

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13. ABSTRACT

A new approach to generating high-velocity air flows with very low ambient dissociation levels is discussed. Briefly, the approach utilizes a nonsteady isentropic compression wave which is focused through an area contraction to accelerate and compress the test gas. This processed gas may be used directly as a test medium or may be allowed to expand nonsteadily through the expansion wave which appears at the focal point of the compression wave system. In either case, the flow may be further expanded in a nozzle if so desired. The advantages and disadvantages of both methods of operation are discussed.

The problem of generating the required wave motion is presented in some detail and preliminary studies of several possible driving techniques are summarized.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Isentropic Compression Gasdynamic Facilities Hypervelocity Flow Nonequilibrium Airflow						

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